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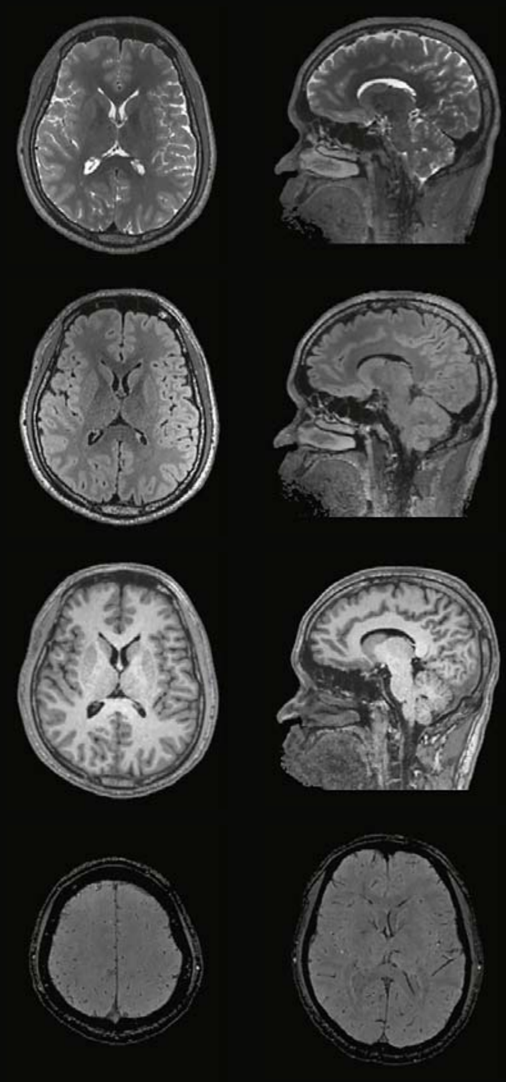

Re-Envisioning Low-Field MRI

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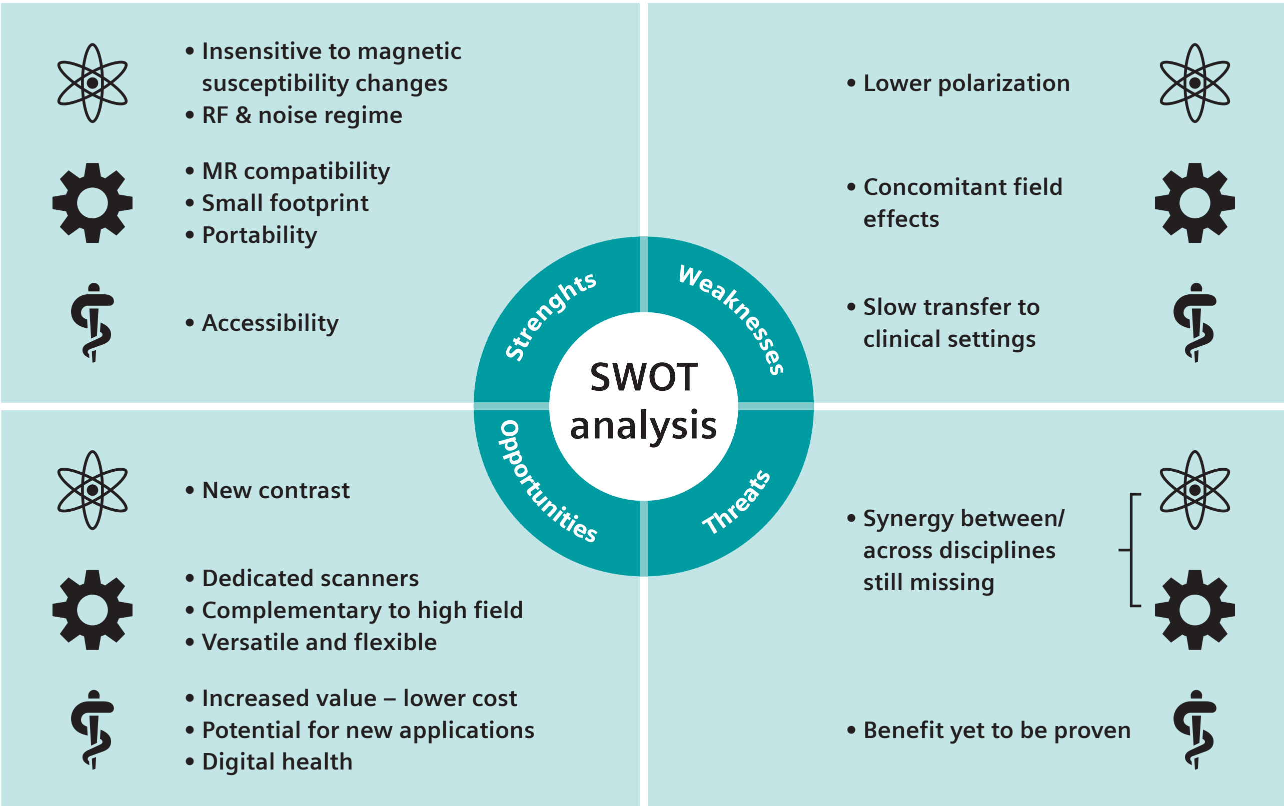
The Center for Adaptable MRI Technology (AMT) aims to develop disruptive MRI technology to push the boundaries of diagnosis and monitoring in environments and settings usually out of reach. This task faces at least two major challenges.

The first concerns scaling down and opening up the MRI device. One way to achieve this is to leverage magnetic field strengths at lower orders of magnitude than today's MRI devices, which are particularly heavy and expensive, have extreme siting requirements and high costs, and offer limited access for patients.

The second concerns enhancing the flexibility of MRI. The AMT Center aims to develop methods and instruments that perform in heterogeneous environments and compensate for the impeded signal sensitivity naturally available at lower magnetic fields.

The AMT center's research focuses on four different areas:

1. **Tools and methods for low-field MRI:** With a unique platform including multiple scanners operating at variable fields, this area focuses on developing new MR sequences and detectors for specific applications.
2. **Image-guided therapies:** Research in this area involves the development of MRI sequences and instruments compatible with therapeutic settings/devices.
3. **Quantitative and functional MRI:** These techniques will provide quantified metrics of organ function.
4. **Fast multiparametric MRI:** The aim here is to accelerate quantitative diagnosis.



1 SWOT analysis of low-field MRI.

MRI has without doubt revolutionized medical imaging. In addition to delivering anatomical images with incomparable soft-tissue contrast, it also enables quantification of metabolic processes and of physiological and mechanical properties in a completely non-invasive and non-ionizing manner. In the late 1990s, the progress made in sequence development, hardware, and computing capabilities even led users to believe that MRI might ultimately replace all other imaging and diagnostic modalities [1].

This did not happen, however, for a number of reasons: The signal in conventional MR techniques comes from the spin polarization of hydrogen nuclei present in the body, and the Boltzmann law defines the total magnetic moment usable for nuclear magnetic resonance (NMR). Despite a high natural abundance and gyromagnetic ratio of ^{1}H nuclei, the sensitivity in NMR is known to be low, particularly when compared to other imaging modalities. In addition, spatial encoding is a necessity, as direct imaging with electromagnetic wavelengths much larger than the human body and individual body parts is not allowed, making MRI a rather slow technique.

Other reasons why MRI has stalled with regards to certain applications include the very important fact that, in parallel to developments in MRI, major technological progress has also been achieved in most other imaging modalities. In addition, MRI scanners as we know them today have mostly remained one-size-fits-all devices, confined to use in radiology departments and within specific and restricted environments. While many clinicians' needs (including those outside of radiology) and potential patient benefits have therefore been overlooked in MRI over the years, they have been addressed, at least partially, using ultrasound or X-ray devices across a large spectrum of applications. The reasons why MRI has not embraced such paradigm shifts are diverse. They are most likely financial and cultural, and certainly not limited to constraints of technical feasibility. We will try to describe why the MRI paradigm could now be at a turning point and why re-envisioning low-field MRI could play a role in the changes to come.

The right time

The advantages of low-field MRI have been highlighted multiple times in recent decades, but the technique has never succeeded in spreading to clinical settings. Recent work in the field shows that the MRI community is entering another of these cycles, and one may wonder why this new decade should be more favorable for a breakthrough in low-field MRI. We see two main reasons for this to be the case. The first is based on technological progress and developments made in the last 40 years, not only with respect to magnetics, but also concerning power electronics, RF detection, sequence programming, and image processing. Altogether, these developments have proven that magnetic field alone is not the key to good quality images. This is easily visible if one compares the first images acquired at 1.5T in the 1980s with today's routine scans. Another factor that could encourage the deployment of low-field MRI today is the increased awareness that one-size-fits-all scanners cannot help in all circumstances. As an example, many groups are now developing mobile, point-of-care solutions [2–6] that leverage low-field technology. These groups include teams that earned their reputation from their work at ultra-high magnetic fields. This recent trend may indicate that low-field MRI should no longer be considered a niche.

More concretely, time is also crucial in MRI when it comes to the signal-to-noise ratio (SNR). Since the early days of MRI, engineers and physicists have pushed high-field MRI because it provides higher polarization and higher spectral dispersion, which respectively enable higher SNR per unit time and advanced spectroscopy measurements. In the past, basic imaging sequences were used, but they were obviously not as time efficient as today's standards. Over the years, researchers and scientists have developed advanced acquisition schemes that are routinely used today and have improved the image quality in terms of sharpness, contrast, and also speed. It is rather challenging to directly compare past and current performance based on the heterogeneous information available in the literature. If, however, we (very roughly) assume equivalent SNR and contrast-to-noise ratio, one could compare the SNR per unit time and volume of T2-weighted images acquired in the human brain in 1986 [7]. The outcome yields an acceleration factor superior to 7 for an equivalent voxel size. Wald recently highlighted the various revolutions, beyond the magnetic field, that have occurred in MRI [8]. When combined with lower magnetic field strengths, these revolutions would certainly democratize MRI and make it as versatile as other established modalities (e.g., ultrasound or X-ray technologies). After 40 years of development, it is now becoming clear that the quest for ever-higher field strengths is weakening, leaving room to also explore the physics of low- to ultra-low-field MRI.

The right tool

High-field MRI has transformed the medical imaging landscape, producing images with high soft-tissue contrast in reasonable acquisition times. Beyond simple images, MRI has ventured into a broad range of areas, from time-resolved 3D imaging of moving body parts to imaging of cerebral function, flow and motion, and even temperature changes within interventional settings. This progress is unfortunately restricted to cases that are compatible with conventional MR environments, and access is limited to applications that can be physically bound to radiology suites. Immense efforts have been invested in developing MR-compatible devices and surgical instruments that continue to broaden the range of envisioned applications within MRI facilities. However, they also raise the overall cost of an MRI examination. This ultimately affects accessibility from a financial perspective, and therefore makes MRI an even more exclusive modality.

It is known that lowering magnetic field strength is a path to relaxing both engineering and siting requirements for MRI scanners. It also comes with many extra benefits, such as a smaller footprint and lower power consumption, fewer magnetic susceptibility issues, and increased compatibility within a variety of environments. However, lowering the magnetic field naturally leads to lower nuclear spin polarization and therefore reduces SNR per unit time, raising questions about low-field capabilities and opening debates about what would define the most relevant field strengths in clinical settings. The latter point is worth commenting on, as this type of debate only exists in the MRI community. X-ray and ultrasound have already been successfully adapted to fit different applications, while technological progress in MRI (for the most part) continues to revolve around the same 30-year-old geometry that fits all body parts and sits in a complex shielded environment. Over the years, scientists have explored NMR at different magnetic field strengths, yet these have almost exclusively been higher-field regimes, up to what are now commonly called the ultra-high fields (7T and higher). Beyond sensitivity and potential achievable resolution, the main advantages offered by these regimes mostly relate to metabolic imaging and susceptibility mapping. Surprisingly, the discussion about field strength at the other end of the spectrum has never really been fueled, and is often reduced to practical considerations. In most minds today, low-field MRI is restricted to mid-field MRI (from 0.25 to 1.0T); these open geometries are mainly justified for obese and claustrophobic patients, or to guide biopsies. This is a valid approach, but possibly not disruptive enough for real breakthroughs. Indeed, such field strengths are still too high to harness the real advantages of low-field MRI, and siting requirements (in particular for permanent magnet designs) are still the same as for high-field scanners. The next section will set out the pros and cons of low-field MRI, and describe how it can complement conventional MRI.

Low-field MRI under the microscope

A simple way to illustrate and discuss the potential development of low-magnetic-field MRI is using a SWOT analysis. A summary is presented in Figure 1, and the different aspects are discussed below.

Strengths

Physics

Using lower field strengths has the obvious advantage of reducing MR-compatibility issues and susceptibility artifacts. Images are no longer prone to chemical shift artifacts, imaging can be performed near implants, and MR-guided procedures become possible. Contrast is also a key feature in low-field MRI and will play a major role in how fast the technique is adopted in clinical settings. It is well known from the early days of MRI that lower field strengths offer a wider dispersion in T1 relaxation times [9] and have the potential to reveal endogenous contrasts that are relevant for very specific applications. As low-field MRI has quickly been abandoned in the past, this area of research is still rather untouched and deserves to be explored. Recent work from Broche and colleagues supports this fact and shows different T1 behaviors during Fast Field-Cycling (FFC) experiments applied to different human body parts *in vivo* [10]. Another major advantage concerns noise domination in different frequency regimes [11]. Sample noise dominates at high field and can be neglected at low field, meaning that the noise level can be favorably influenced by adequately designing and building the different elements of the acquisition chain. Finally, specific absorption rate (SAR) is not an issue in low-frequency regimes.

Engineering

Magnetic field strength is what currently drives the cost of MRI machines. Reducing field strength has a direct impact on cost, as it enables technological solutions in magnet construction that no longer require superconductive technologies and cryogenics. New magnet geometries could be designed (moving away from the current one-size-fits-all design) and MRI technologies could be adapted to dedicated applications. Finally, shielding will not be as demanding as it is today, enabling multiple scanners with smaller footprints to be deployed in a given area [12, 13].

Weaknesses

Physics and engineering

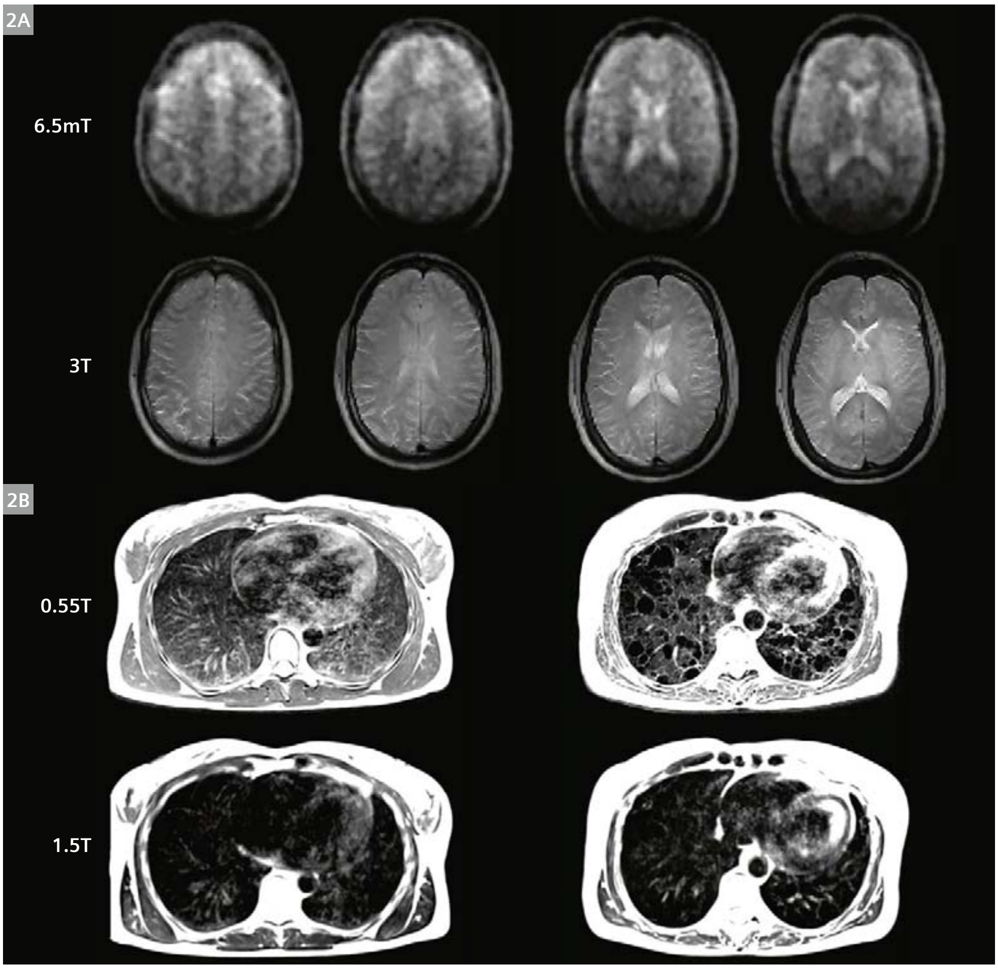
As already mentioned, the major limitation of low-field MRI is that its nuclear polarization is intrinsically lower than conventional MR, which naturally leads to lower SNR per unit time if embraced in the same way as for high-field MRI. Another weakness is the maximum magnetic field gradient strength achievable at a given static main magnetic field, B_0. If gradient strength cannot be increased to achieve finer spatial resolutions because of concomitant field effects, time is the only way of achieving smaller voxel sizes, and this will negatively impact total acquisition times. However, this can also be seen as an opportunity to develop research into these types of regime.

Medicine
As mentioned in the Strengths section, contrast could be a game changer at low field. This added benefit opens up new perspectives, but it also requires radiologists to adapt their skills for interpreting images according to the field strength. Perhaps other practitioners will also have to develop basic skills for reading images, if the goal is to decongest radiology departments using point-of-care units. Multisite studies will be needed to fine-tune the learning process, and this step will inevitably slow down the transfer of technology to clinical routine. It goes without saying that the technology will also need to prove useful in order to attract physicians' interest and maximize their learning curve.

Opportunities

Physics, engineering, and computing
MRI has made many technological leaps forward since it was first introduced in the 1970s, and images produced almost 30 years ago at 1.5T look very different than those obtained today. Low-field MRI can benefit from all these technological advances, as illustrated in two recent papers: Sarracanie et al. performed a six-minute 3D scan of the human brain *in vivo* at 6.5mT using time-efficient b-SSFP sequences and custom-built low-frequency RF resonators [6] (see Figure 2A). In a 2019 publication in Radiology, Campbell and colleagues showed very promising images of different body parts using a mid-field scanner operating at 0.55T[1]. The authors employed a commercial 1.5T scanner with a ramped-down field, existing RF coils simply detuned to the corresponding Larmor frequency, and state-of-the-art MR sequences [14] (c.f. Figure 2B). These recent works show that, rather than being considered as a niche, low-field MRI should perhaps now be viewed as a serious contender in the field of medical imaging.

Applications
Various applications have been described in the past [15]. We will focus only on recent research efforts. Portable and point-of-care devices appear to offer the most promising benefits when considering low magnetic field strengths.



2 Images acquired recently at lower field strengths: **(2A)** Brain images from Sarracanie et al., acquired in the same volunteer at 6.5mT (upper row) and 3T (bottom row) [6]; **(2B)** T2-weighted lung images acquired at 0.55T and 1.5T in a healthy control (left) and in a patient with lymphangioleiomyomatosis (right) [14]. *(2A) Images modified from [6], head under Creative Commons license CC-BY 4.0; (2B) images modified with permission from [14].*

[1]*Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

Publications on this topic, as well as new sessions at international conferences, are good indicators of this current trend [2–6, 16–18]. Interventional MR, and lung and multimodal imaging are also relevant applications, as low-field techniques lower the MR-compatibility hurdle and reduce magnetic susceptibility artifacts [14, 19–24]. The risk-benefit balance is another key criterion guiding the use of imaging modalities, and while MRI is considered very safe, it is usually not indicated in patients with implanted cardiac devices, or in pregnant women and neonates. Lower magnetic field strength, with its intrinsic SAR reduction, could prove extremely useful for these patients and improve their outcomes. Finally, future directions will be defined along the way, as new contrast might reveal key applications for low-field MRI. Even considering that scientists cannot currently reach spatial resolutions equivalent to those of conventional scanners, we already have indications that low-field MRI could provide high-sensitivity, high-specificity diagnoses in patients with cancer, stroke, osteoarthritis, or edema [10]. Has the spatial resolution of nuclear medicine ever been discussed for cancer diagnosis? This is a path worth exploring.

Value

Value in MR has attracted interest recently and is being discussed by all parties, including academics, clinicians, radiologists, and MRI vendors. The topic was discussed during a three-day ISMRM workshop in 2019. It was addressed from different angles with a focus on exploring opportunities to increase value in MRI, with value defined as the ratio of outcome to cost. Cost is probably the main barrier, as MRI machines are usually worth about €1 million per tesla. As a result, MR examinations have been shortened drastically so that more patients can be scanned per day, leading to an increase in burnout cases among radiologists and technologists [25]. Surprisingly, examination time was the first aspect to be adjusted in order to reduce cost. This completely overlooked the fact that, for a given scanning protocol, variability exists that is caused by human, not technical, factors [26]. What if this paradigm were to change and the direct cost of MRI scanners was reduced instead of examination time? Staff would be under less pressure, more time would be allocated per patient, and/or more personnel could be hired. Again, one way to decrease the cost of an MRI scanner is to lower the magnetic field strength – not only for permanent magnets but also for resistive or hybrid technologies – to avoid dealing with heavy equipment that requires special handling and siting. In addition to reducing costs, lowering field strength is also relevant because it enables siting in areas with restricted space [12, 13], making MRI more accessible in highly populated regions. Market trends alone indicate a clear need for this technology, as mid-field scanners represent about 50% of sales in Asia [27], against 6% in Europe and North America [28]. The added value of ubiquitous MRI could also play an important role in the new realm of digital health, producing truly big data and channeling artificial intelligence. Ultimately, true value would stem from MRI becoming available in places where it is currently not an option.

Threats

History shows that the major threat regarding low-field MRI is the lack of added outcome to increase the overall value of the technique. Lowering cost is clearly crucial, but it is not enough to convince clinicians and governments to use different tools if the benefit for the patient does not increase significantly. Various past attempts have shown a high potential for creativity and originality in MRI developments, especially in magnet design. However, the images often had low SNR and took an extremely long time to produce. The technology now seems able to circumvent such limitations. The capacity to secure better outcomes at low field will also come from a general willingness to pool skills and expertise across various fields, from combining state-of-the-art MR sequences with the best RF detectors and magnet design, and from advanced computing resources. Only then will low-field MRI achieve its breakthrough.

Conclusion

Many indicators show that MRI is ready to undergo a transition. In the near future, we anticipate that there will no longer be one type (or just a few types) of MRI, but rather a range of systems that can serve a variety of applications and needs. Since its invention, MRI has made tremendous technological and methodological progress, delivering highly valuable images that provide anatomical, functional, and metabolic information. Yet this information is available in restricted areas only, either due to affordability or logistics, since MRI is expensive and highly demanding in terms of siting and compatibility. The original landscape has already started to evolve, and economically powerful actors are showing that alternative models are possible, with lower-field MRI already earning large market shares. MRI must become more accessible, widespread, and versatile in order to benefit patients as much as possible. The need for low-cost, high-performance low-field MRI is clear, and it is only a matter of time before new technologies become available.

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